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Temporal decision-making factors in risk analyses of dynamic positioning operations

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ABSTRACT

Nearly all dynamic positioning (DP) operations are characterized by limited time available for the DP operator to detect and act upon a loss of position. Collision risk is analyzed with a quantitative risk analysis, which usually does not analyze the human contribution to the risk picture, but rather uses estimates. The objective of this paper is to evaluate the way time (e.g. available time, time required, perceived time available and perceived time required) is addressed in risk analyses for oil and gas DP operations and how this affects safety. The study has found that time required can exceed the time available, and that the effects of perceived time available and perceived time required need to be included in human reliability analysis. In general, awareness needs to be raised around the importance of time. This can be done by including the different aspects of time into risk analyses of DP operations so that effective risk reducing measures can be identified. Furthermore, decision support tools should be developed that integrate the dynamics of the vessel movement over time (time available) and the response time of the operator and system (time required) to address not only *what*, and *how* of decision-making, but also *when*.

1. Introduction

The DP system was developed in the 1960's for offshore drilling. Jack-up drilling platforms could no longer reach at the water depths that were being explored and anchoring was not a financially viable option or not possible due to a congested sea bottom. The first DP vessels used analogue systems with no redundancy. Since then the dynamic positioning (DP) system has developed and there are now requirements for redundancy, especially for high-operations inside the 500-meter zone of platforms. DP vessels allow for new types of operations in new areas where it is important to be able to relocate easily and quickly. A DP system is a system capable of controlling a set course, heading or position of a vessel by use of thrusters and propellers and reference systems [33]. DP is now used for a wide variety of operations, such as supply, drilling, shuttle tanker, flotel, construction and heavy-lift, pipe- and cable-laying, survey, anchor handling, diving and Remote Operated Vehicles (ROV), survey, dredging, cruise ship, etc. [10].

The risk associated with DP operations vary concerning the position excursion tolerance and their consequence potential [34]. To illustrate this some examples are provided in Table 1. Four types of DP operations are presented with the distance separating them from the installation: floating production storage and offloading (FPSO) vessel and shuttle tanker (ST) offloading operations, flotel providing additional accommodation for an oil platform, supply operations at an oil platform, and a mobile offshore drilling unit (MODU) operating on DP. The drilling operation's condition differs from the other, because it does not include a collision object, and therefore no separation distance. However, the MODU is attached to the well with, amongst other things, a drill string and riser, the angle of the riser determines the excursion tolerance of the operation. The time available is gathered from previous studies, no information was available for flotel and supply operations. Chen and Moan [5] found that at a separation distance of 80 meters ST operators have 53 seconds to respond to a drive-off in the direction of the FPSO. Hogenboom et al. [11] found that the reaction time between the first and highest alarm level is set to 60 seconds to allow personnel in the moonpool area to evacuate the area to avoid being hit by the drill string in case it get severed.

As indicated in Table 1, distance and time available are linked. A study by Parhizkar et al. [22] found that time available has the greatest effect on collision probability. A combination of weather, thruster forces, and distance will determine how much time a DP operator (DPO) has to react to a loss of position. This requires that the operator is alert

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Table 1
Separation distance for several types of DP operations (* = no data available).

DP operation	FPSO-ST	Flotel-Platform	Supply-Platform	Drilling
Separation distance	80 m	60-70 m	20-30 m	Not relevant
Time available	53 s	*	*	60 s
Excursion tolerance	Hose tension	Gangway	Hose tension and reach of crane	Riser angle dependent on water depth

and vigilant and ready at any time to take over manually from the DP system and move the vessel to a safe location. Of course, there are safety margins in place to "buy" the operator more time to respond and increase the time available. For example, some operations are not allowed on the windward side of an installation to avoid a collision in case of a drift off. A drift-off means that there is insufficient thrust to maintain the target vessel position and as a result the vessel drifts away due to the environmental forces Chen et al. [35]. However, this is not helpful in a drive-off situation, where there is active thrust driving the vessel away from the target position [35] and potentially into the installation. All DP operations are inherently threatened by a loss of position [9].

Yet, the consequences of a loss of position can vary. Some position losses can lead to a collision, others to damage to subsea structures, or (oil) spills due to ruptured hoses. To avoid this from happening there are safety systems in place, nevertheless, the DPO is usually considered the last barrier of defense against a loss of position and in avoiding damages due to a loss of position [9].

A study from Chen and Moan [5] that identified measures to reduce recovery failure for FPSO-ST collision risk found that for some incident scenarios there was insufficient time for the operator to respond successfully to a loss of position. The study recommended to increase the time window for the operator to initiate a recovery action and to provide assistance to reduce the time required to initiate a recovery action. To achieve the first an increase in operating distance to the installation was proposed as well as a change to the setup of the thrusters. Furthermore, to reduce the reaction time of the operator Chen and Moan [5] proposed improved early detection, through preventing operator fatigue, interference from other activities, and providing observation training. They also recommend quick decision-making, to improve this they recommend training, proceduralization and automation [5].

In another study by Chen, Moan and Vinnem [6] DPOs' reaction times were observed in a simulator. In 59 simulator observations of drive-off scenarios for FPSO-ST operations they found that the mean reaction time is 81 seconds, of which 59 seconds are spent detecting the event, and 22 seconds deciding and executing the recovery actions. These reaction times indicate that there is insufficient time available for the DPO to recover from a full-head-on drive off and prevent a collision [6], unless the distance between the FPSO and ST is about 150 m.

To illustrate how time is treated in the various risk assessments a case study was selected for this article. The *Sjøborg* accident [24] was chosen as a case study because it is a recent event that highlights the criticality of time.

The *Sjøborg* supply vessel collided with the *Statfjord A* installation in Norway on 7 June 2019. In the early morning the supply vessel was transferring fresh water, diesel oil and deck cargo. A technical failure meant the load reduction mode was activated on the vessel, reducing power to all its thrusters to 10-15 per cent of the maximum. Power was lost to two of three bow thruster upon which the vessel lost heading and position and drifted against the installation. The *Sjøborg* suffered damages to the mast and equipment above the bridge when they collided with the lifeboat station of the *Statfjord A*, and dents on the starboard aft side where it hit the drilling shaft of the installation.

The Norwegian Petroleum Safety Authority (PSA) lounged an investigation and the data used in this article about the accident is largely based on their accident investigation report [24].

The paper is structured as follows. An overview of how some of the risk analyses address the time elements is presented in Section 2. The methods and analyses used in the paper are introduced in Section 3 together with the results of the various analyses. Section 4 summarizes and discusses the results and presents the recommendations based on the findings of the study. Section 4 also outlines the limitations of the study and the need for future work. Details of the methodology are presented in Section 4. Finally, the conclusions and the contributions of this study are presented in Section 5.

2. Temporal Factors in Risk Analyses

2.1. Quantitative Risk Analysis (QRA) of Collision Risk

Collision risk between vessels and installations has been quantified by estimates of frequency for collision and energy involved in the collision. The models are based on the frequency of failure modes that can lead to collision scenarios and by modeling the resulting course of events. The preferred modeling method varies; commonly fault trees or event trees are used. Historical frequency data is used as input for these models, taking into account operational conditions [16]. The risk models often have flexibility to include human reliability assessments for safety critical tasks [18,26], however, they are not ordinarily included.

Traditionally, the levels of complexity in the models have been kept low to due to low availability of adequate quantitative input estimates. Furthermore, the technical and operational conditions and barriers are taken into account, but they are not able to take a holistic view of the risk picture, nor are they capable of modeling the interaction effects [16].

2.2. Human Reliability Analysis (HRA)

The HRA methods that are considered for this study were selected from the HSE (Health and Safety Executive) review of HRA methods [1]. The requirement for the method was that it is publically available and can potentially be applied to DP operations and does not require expert judgement. Based on these criteria the following methods were considered:

- THERP (Technique for Human Error Rate Prediction)
- HEART (Human Error Assessment and Reduction Technique)
- SPAR-H (Simplified Plant Analysis Risk Human Reliability Assessment)
- ATHEANA (A Technique for Human Error Analysis)
- CREAM (Cognitive Reliability and Error Analysis Method)

In 2017, a research and development project funded by the Norwegian Research Council has developed the Petro-HRA method and guideline [3]. The method was specifically developed to analyze the human reliability of safety critical tasks in the offshore industry. Since it did not exist prior to the United Kingdom HSE review of HRA methods was concluded in 2009, it was not part of that study. However, considering the relevance to this topic and it meeting the requirements set for the selection of HRA methods, it is included in this study.

The selected HRA methods were reviewed based on their inclusion of performance shaping factors (PSFs) addressing time available and perceived time available. The only methods that described both actual and perceived time available are the SPAR-H and Petro-HRA method. A description of how they include time is presented below, an overview of the PSFs and associated multipliers are presented in Table 2 and Table 3.

2.2.1. Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H)

The SPAR-H addresses time mainly in the performance shaping

Table 2
PSFs related to time available/required per selected HRA method.

Method	PSFs related to time available	Multiplier	Level	Level description
SPAR-H	Available time	HEP = 1	Inadequate time	The time margin is negative because less time is available than is required.
		10	Barely Adequate Time	The time margin is zero because the time available equals the time required.
		1	Nominal Time	There is a small time margin because the time available is slightly greater than the time required.
		0.1	Extra Time	The time margin is greater than zero but less than the time required; the time available is greater than the time required.
		0.01	Expansive Time	The time margin exceeds the time required; the time available is much greater than the time required.
Petro-HRA	Time	(HEP) = 1	Extremely high negative effect on performance	Operator(s) does not have enough time to successfully complete the task.
		50	Very high negative effect on performance	The available time is the minimum time required to perform the task or close to the minimum time to perform the task. In this situation the operator(s) has very high time pressure or they have to speed up very much to do the task in time.
		10	Moderate negative effect on performance	The operator(s) has limited time to perform the task. However, there is more time available than the minimum time required. In this situation the operator (s) has high time pressure, or they have to speed up much to do the task in time.
		1	Nominal effect on performance	There is enough time to do the task. The operator(s) only has a low degree of time pressure, or they do not need to speed up much to do the task. When comparing the available time to the required time the analyst concludes that time would neither have a negative nor a positive effect on performance.
		0.1	Moderate positive effect on performance	There is extra time to perform the task. In this situation the operator(s) has considerable extra time to perform the task and there is no time pressure or need to speed up to do the task in time.
		1	Not applicable	PSF is not relevant for this task or scenario.

factor (PSF) available time. The PSF looks at the available time relative to the time that is required to complete the task, so there could be an extra time margin, see Table 2 for a description of the levels and multipliers. The method uses different time PSF descriptions for diagnosis and action events. Diagnosis events often have a wider time range in which they can be performed. It is presumed that a decision can be made quickly, if necessary. However, when determining the nominal time needed to make a decision, this should be based on systematic and thoughtful thinking and individual differences will have to be averaged out [30]. The available time PSF does not consider aspects of perceived time pressure by the operator. Actual and perceived time pressure induce stress, and are therefore be assessed under the stress/stressor PSF [30].

2.2.2. *Petro-HRA*

The method is based on the SPAR-H method, but it comes with an extensive guideline describing not only how to conduct a HRA from start to finish, but also how to integrate the HRA with the QRA process [3]. The Petro-HRA method distinguishes between objective time available and the subjective experience of time available. Objective time available is treated under the PSF: time, and the subjective experience of time available under the PSF: training/experience [3].

2.3. *Dynamic risk assessment*

Dynamic risk models have been developed to analyze operational risk. Dynamic risk assessments updates risk estimates based on performance of the control system, safety barriers, inspection and maintenance activities, human factors, and procedures. Almost all qualitative and quantitative risk analysis methods involve hazard identification, risk assessment, and evaluation of control measures [19]. Dynamic risk assessment adds a phase of monitoring and assessing abnormal conditions to revise the estimated risk. This largely describes the role of the DPO, where the DP operator is monitoring the DP systems' performance and on the look-out for abnormalities or failures [9]. There have been several contributions in recent years that propose and promote dynamic risk assessment methods [14,15,21].

The integration of dynamic risk assessment and management can support the decision-making process by providing a real-time risk estimate [15]. Furthermore, appropriate model selection and sensitivity investigation techniques are required for decision support [7]. Additionally, advanced data acquisition systems for providing real-time input to quantitative risk management are needed. Furthermore, model sensitivity to uncertain input data needs to be considered. Vinnem et al. [29] proposed an online risk management framework for DP operations, that takes these concerns into consideration.

However, in most of these studies, response time is not considered in the dynamic risk model or decision-making model. Nevertheless, time is a critical factor in nearly all loss of position incidents, what is more the decision-making process takes time. Time required to handling a loss of position scenario and the consequences of each decision scenario are not

Table 3
PSFs related to perceived time available/required per selected HRA method.

Method	PSFs related to perceived time available	Multiplier	Level	Level description
SPAR-H	Stress/ stressor	5	Extreme	A level of disruptive stress in which the performance of most people will deteriorate drastically, the so-called stress performance cliff. This is likely to occur when the onset of the stressor is sudden and the stressing situation persists for long periods. This level is also associated with the feeling of threat to one's physical well-being or to one's self-esteem or professional status, and is considered to be qualitatively different from lesser degrees of high stress (e.g., catastrophic failures can result in extreme stress for operating personnel because of the potential for radioactive release).
		2	High	A level of stress higher than the nominal level (e.g., instruments with anomalous readings or unexpected alarms; loud, continuous noise impacts ability to focus attention on the task; the consequences of the task represent a threat to plant safety). This level basically encompasses any situation where there is a perceived threat that can result in significant health or financial consequences (such as loss of the plant).
		1	Nominal	The level of stress that is conducive to good performance. Also, this level should be assigned whenever stress is judged to not be a performance driver.
		1	Insufficient Information	If you do not have sufficient information to determine if this is a performance driver or to choose among the other alternatives, assign this PSF level. Note that the multiplier is the same as for Nominal.
Petro-HRA	Training/ experience	(HEP) =1	Extremely high negative effect on performance	There is a strongly learned knowledge or skill (either from experience or training) that is a mismatch with the correct response to this task step in this scenario. An example could be that the operator(s) during experience or training has developed a strong mindset about the development of a scenario and actions that do not fit with the scenario in question and therefore cannot be expected to perform the task correctly.
		50	Very high negative effect on performance	The operator(s) does not have any experience or training and does not at all have the necessary knowledge and skills to be prepared for and to do the task(s) in this scenario.
		15	Moderate negative effect on performance	The operator(s) has low experience or training and does not have the necessary complete knowledge and experience to be prepared for and to do the task(s) in this scenario.
		5	Low negative effect on performance	The operator(s) has experience or training but this is lacking, and they do not have the complete knowledge and experience to be fully prepared for and to do the task(s) in this scenario.
		1	Nominal effect on performance	The operator(s) has experience and/or training on the task (s) in this scenario and has the necessary knowledge and experience to be prepared for and to do the task(s) in this scenario. Experience/Training does not reduce performance nor to a large degree improve performance.
		0.1		

(continued on next page)

Table 3 (*continued*)

Method	PSFs related to perceived time available	Multiplier	Level	Level description
			Moderate positive effect on performance	The operator(s) has extensive experience and/or training on this task and the operator(s) has extensive knowledge and experience to be prepared for and to do the task(s) in this scenario.
		1	Not applicable	PSF is not relevant for this task or scenario.

independent. Different combinations of factors will affect the decision scenarios and will result in different required time and consequences of the decision. This needs to be addressed in dynamic decision-making models and they need to be risk based. In addition, even though many contributions have been proposed to risk-based decision-making models, the dynamic dependency of the response is barely included. The decision-making process is highly time dependent and changes over time according to system operational and environmental conditions. Moreover, system operation is dynamically affected by decisions. In order to establish an accurate decision-making model these interactions should be considered as well. The interactions of the system and the decision-making process in a dynamic environment is considered in a study carried out by Chang and Mosleh [4].

Parhizkar et al. [23] have developed a decision-making safety assessment framework and human response time (HRT) model that consider the dynamic nature of decision scenarios and their interdependencies. In the proposed framework, the scenarios' effectiveness are calculated as a function of the previous events and occurrence time [28]. As a result, in addition to the dynamic of the system, a decision scenario depends on the dynamic nature of the decision-making process. Event sequence diagrams (ESD) are used to predict the dynamic safety level of incidents in complex systems [31]. The ESD present the logical relations among events in the system. The framework utilizes ESD in combination with fault trees and Bayesian networks (BNs) to estimate the occurrence frequency or probability of the system hazardous events and consequences, and to address the root causes to system hazardous events.

2.3.1. Dynamic Simulation

As mentioned above time available is critical in determining the probability for success of avoiding a potential collision or other negative consequences of a loss of position. A dynamic simulator can calculate the remaining available time, based on operation and environmental conditions [25]. The simulator gathers input from DP system components' status (engines, thrusters, control system, etc.), environmental conditions (wind force and direction, wave force and direction, etc.), and vessel and DP type [25]. For instance, some DP operations utilize a specific operating guideline (SOG) that predefines the excursion limits into yellow and red alarms [9]. The remaining available time for the DP operation is then equal to the minimum required time that the vessel reaches the outer "red" limit for position excursion. Most supply vessel operations on the Norwegian Continental Shelf (NCS) do not have a SOG, and the time available needs to be calculated for the

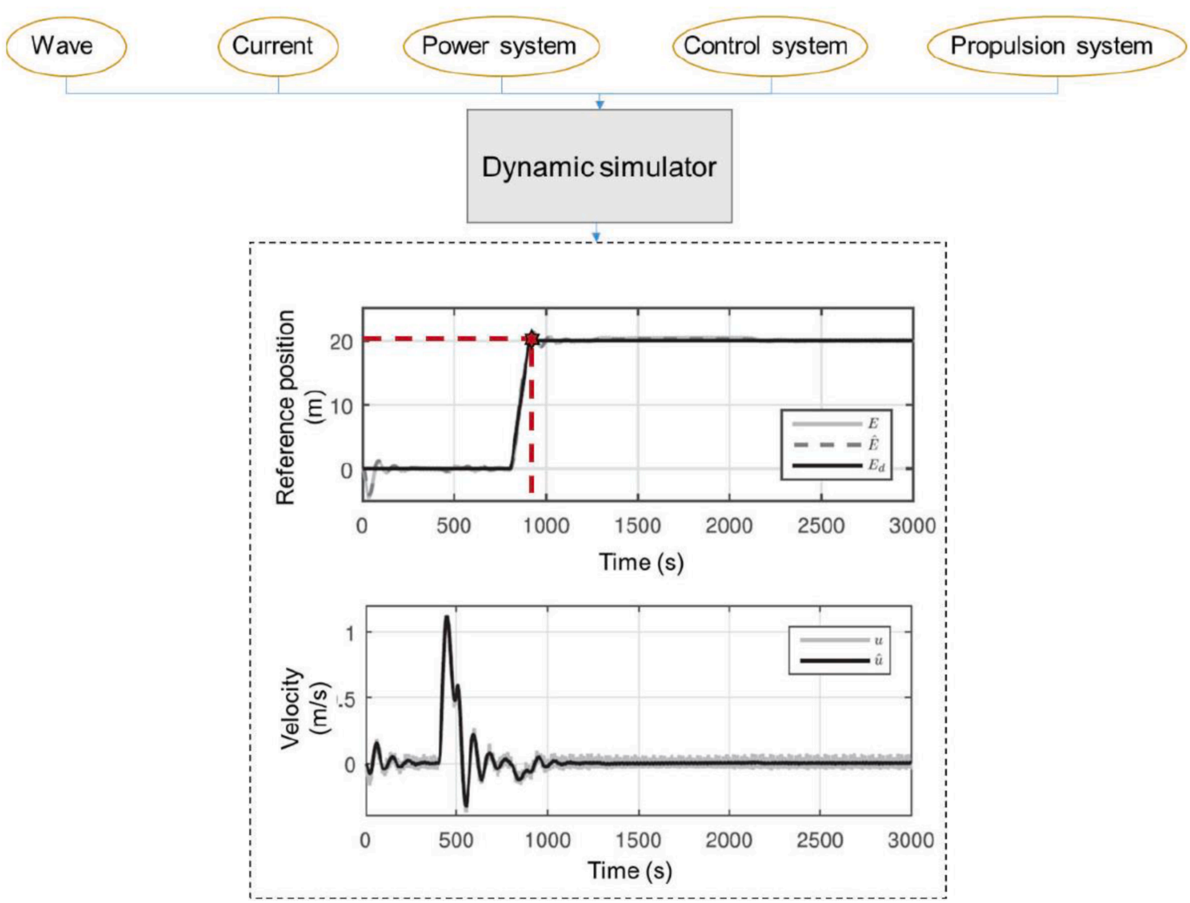

Fig. 1. Example of output from the dynamic simulator (adapted from [22]).

“point-of-no-return”. The point-of-no-return refers to the time until the vessel reaches a position from which a collision becomes inevitable due to remaining time until collision, available thruster and environmental forces, human and technical reaction times.

Fig. 1 depicts an example of the output from the dynamic simulator. The dynamic simulator has the potential to display the displacement of the vessel over time based on real-time input data. The objective of utilizing the dynamic simulator in such a capacity would be to give decision support to the DPO. As can be seen, the operational and environmental conditions of the DP system serve as input to the dynamic simulator, including wave and current data, as well as status and characteristics of the power system, control system and propulsion system [32]. The dynamic simulator then calculates the position and velocity of the vessel over time. In the example portrayed in Fig. 1, the DP vessel is 20 meters away from a red limit. The red-dashed line symbolizes that limit, and time available until passing the red limit is estimated to be 900 seconds.

3. Method and Results

3.1. STEP timeline analysis of the Sjøborg accidents

The STEP (sequential timed events plotting) method is used to analyze the timeline of the Sjøborg accident. The STEP method is developed by Hendrick and Benner [8]. STEP is a systematic process for accident investigation based on multi-linear event sequences, and a process view of the accident events.

The STEP diagram presents the timeline of events, each row represents a different actor that plays a role in the accident sequence. The actors can either be human or an controller. The columns represent the timeline. The time scale does not have to be on a linear scale. The main point of the timeline is to present the order of events and how they evolved relatively in terms of time. The flow of events indicated by the arrows, illustrate the affect of one actor’s actions on other actors’ actions. There are two specific types of events: the initiating event, the event identified as the upset to normal operations and that requires a response to avoid undesirable outcomes, and the end event, the events that presents the end of the accident sequence either the consequence (e.g. collision) or return to safe state (e.g. arrival at safe location).

To analyze the Sjøborg accident the accident investigation report from the Petroleum Safety Authority [24] was used as input.

3.1.1. Results

The Sjøborg accident was analyzed with a STEP worksheet (see Fig. 2). The timeline is in minutes and takes the loss of position as T = 0 (corresponding to actual time 01:50 – seconds not available from the report, see below). The results of the analysis are presented in Table 4. The accidents is broken down into an initiating event, contributing events, and the end event. The relevant actors have been identified for each event. The time of the events can be found in the last column in the Table.

3.2. Time required

In order to establish an estimate for time required a task analysis and timeline analysis were performed. A hierarchical task analysis (HTA; [27]) was developed based on the Sjøborg accident. The HTA analyzed two potential scenarios: the DPO detects the first alarms and decides to stop the operation, and the DPO notices the drift-on and tries to get to a safe location. The HTA was then transferred into a tabular task analysis (TTA; [27]) to gather information on the critical timeline of the scenarios and provide structured estimates for time required for the two scenarios. The HTA is based on a cognitive model of detect, diagnose, decide, and execute/act (see Fig. 3).

The timeline analysis requires a complete task analysis, information gathered from a site visit, input from experienced operative personnel, data from relevant drills/trainings, incident reports and investigations [3].

According to Bye et al. [3] the timeline analysis should consist of the following seven steps:

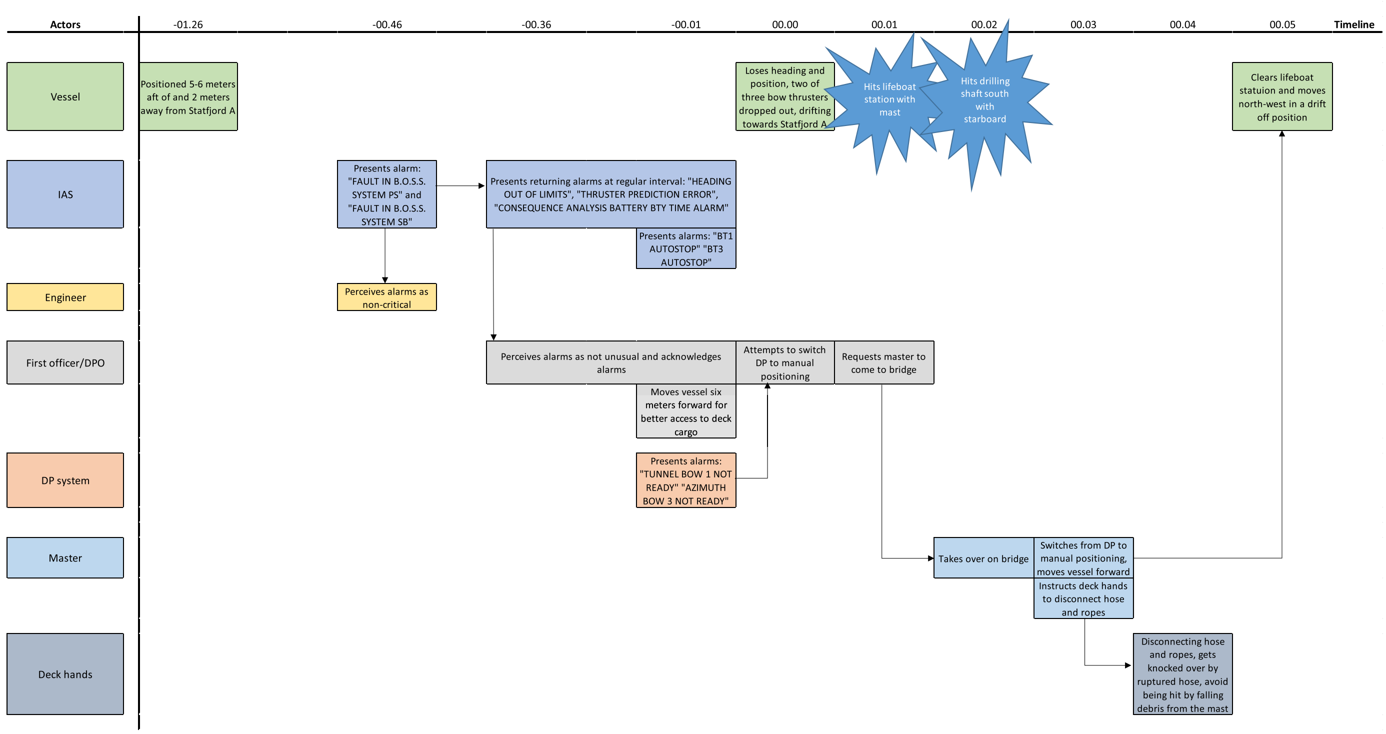

Fig. 2. STEP analysis of the Sjøborg accident based on events described in the investigation report from the PSA [24].

Table 4
Results of the Sjøborg accident analysis based on the investigation report [24].

Event sequence	Actor	Event description	Time of event (hh:mm)
Context	Vessel	Positioned 5-6 meters aft of and 2 meters away from Statfjord A	00:24
Initiating event	IAS (Integrated Automation System)	Presents alarm: "FAULT IN B.O.S.S. SYSTEM PS" and "FAULT IN B.O.S.S. SYSTEM SB"	01:04
1	Engineer	Perceives alarms as non-critical	01:04
2-A	IAS	Presents returning alarms at regular interval: "HEADING OUT OF LIMITS", "THRUSTER PREDICTION ERROR", "CONSEQUENCE ANALYSIS BATTERY BTY TIME ALARM"	01:14-01:49
2-B	DPO/first officer	Perceives alarms as not unusual and acknowledges alarms.	01:14-01:49
3-A	DPO/first officer	Moves vessel six meters forward for better access to deck cargo	01:49
3-B	IAS	Presents alarms: "BT1 AUTOSTOP" "BT3 AUTOSTOP"	01:49
3-C	DP SYSTEM	Presents alarms: "TUNNEL BOW 1 NOT READY" "AZIMUTH BOW 3 NOT READY"	01:49
4	Vessel	Loses heading and position, two of three bow thrusters dropped out, drifting towards Statfjord A	01:50
5	DPO/first officer	Attempts to switch DP to manual positioning	01:50
6-A	DPO/first officer	Requests master to come to bridge	01:51
6-B	Vessel	Hits lifeboat station with mast	01:51
7-A	Master	Takes over on bridge	01:52
7-B	Vessel	Hits drilling shaft south with starboard side aft	01:52
8	Master	Switches from DP to manual positioning, moves vessel forward	01:53
9	Master	Instructs deck hands to disconnect hose and ropes	01:53
10-A	Deck hands	Disconnecting hose and ropes, gets knocked over by ruptured hose, avoid being hit by falling debris from the mast	01:54
10-B	Vessel	Diesel hose ruptures	01:54
End event	Vessel	Clears lifeboat station and moves north-west in a drift off position	01:55

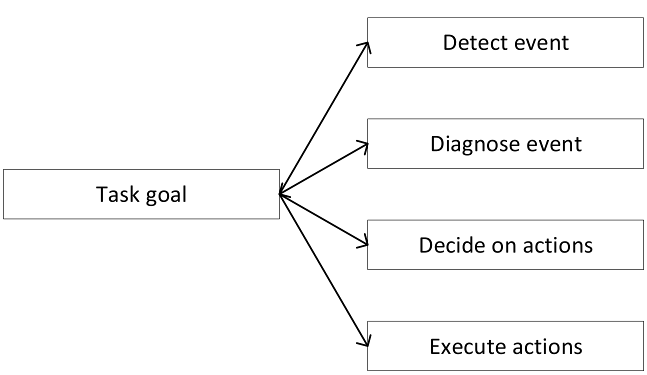

Fig. 3. Basic cognitive model of operator tasks.

1 List task steps on the first level in the task analysis (i.e., level 1.0) vertically together with who is responsible for carrying out each task.
2 Draw a timeline horizontally using a scale suitable for the duration of the task and scenario being analyzed. Time = 0 is defined by the physical initiation of the event.
3 Include the next point in time, which will be the first cue presented to operators indicating the initiating event. This is typically an alarm, a visual observation of the event, or a physical sensation.
4 Discuss the duration of each following task step using the details captured in the task analysis.
5 Time estimates are recorded in a table
6 Conclude when the last task required is successfully accomplished. The duration from Time = 0 to Time = task completion equals the estimated time required.
7 For completeness, mark the time when the effect of the task is evident

The HTA was verified during three interviews with male interview subjects who have on average 20 years' experience with supply operations on the NCS. No identifying information about the interview subject was recorded. After the HTA was verified, the TTA was completed and information for the timeline analysis was gathered. The interviews lasted 1,5 hours each and took place via video conference were conducted June-August 2020.

3.2.1. *Results time required*

Time required is established through a breakdown of two scenarios: early warning intervention and recovery of situation. The early warning intervention starts with the same initiating event as the Sjøborg accident, but the DPO then decides to abort the operation based on the first alarms coming in on the IAS (Integrated Automation System) and move the vessel to a safe location. The HTA of this scenario can be found in Fig. 4. A further analysis of these tasks can be found on the TTA in Table 5.

The second scenario, the recovery actions, starts with the initiating event of the alarms of the two thrusters not being ready, the DPO then recognizes the situation and immediately decides to switch the DP systems to manual and move to a safe location. The HTA of this scenario can be found in Fig. 5. A further analysis of these tasks can be found on the TTA in Table 6.

The three interview subjects all agreed on the identified tasks and provided similar time estimates. A method for aggregating expert opinions into a group fuzzy consensus opinion [13] was considered. However, due to the high level of consensus on the time estimates (66% were identical), the median of the estimates was chosen for further analysis. The estimates from each interview are provided in Table 5 and Table 6.

Based on the tasks identified as the critical path a timeline was made for the first scenario (see Fig. 6). The time estimates are based on the assumption that all involved personnel are alert and available. Median time estimates from the interviews were used for the timeline as the estimates were very similar. As mentioned in Table 5, the communication with the engineer (task 4 in Fig. 6) about the problem will take longer if the electrician needs to be called, but the scenarios assume that the engineer communicates to the bridge that the cause of the problem is unknown. Additionally, the communication with the crane driver estimate is also optimistic (task 7 in Fig. 6). Communicating the information itself should not take longer than a few seconds, but this is assuming that the crane driver answers the call immediately, which is not always the case due to the traffic on the channel. In Fig. 6, the time estimate for the entire scenario starting with the detection of the alarms and ending in arrival at the safe location (100 meters forward from the installation in a drift-off position) is around 260 seconds.

A separate timeline was made for the second scenario (see Fig. 7), which is based on the critical path of the identified recovery actions (see Table 5). This scenario starts with the vessel losing thruster capacity and starting to lose its position and ends when the vessel has arrived at a safe location, which is also assumed a 100 meters forward from the installation in a drift-off position just like the previous scenario. The time estimates are based on the assumption that the DPO is alert and aware of the operating situation. Median time estimates from the interviews were used for the timeline as the estimates were very similar. The timeline shows that upon receiving the alarms for lost thrusters the operator discusses and diagnoses the situation with DPO 2 and then decides that

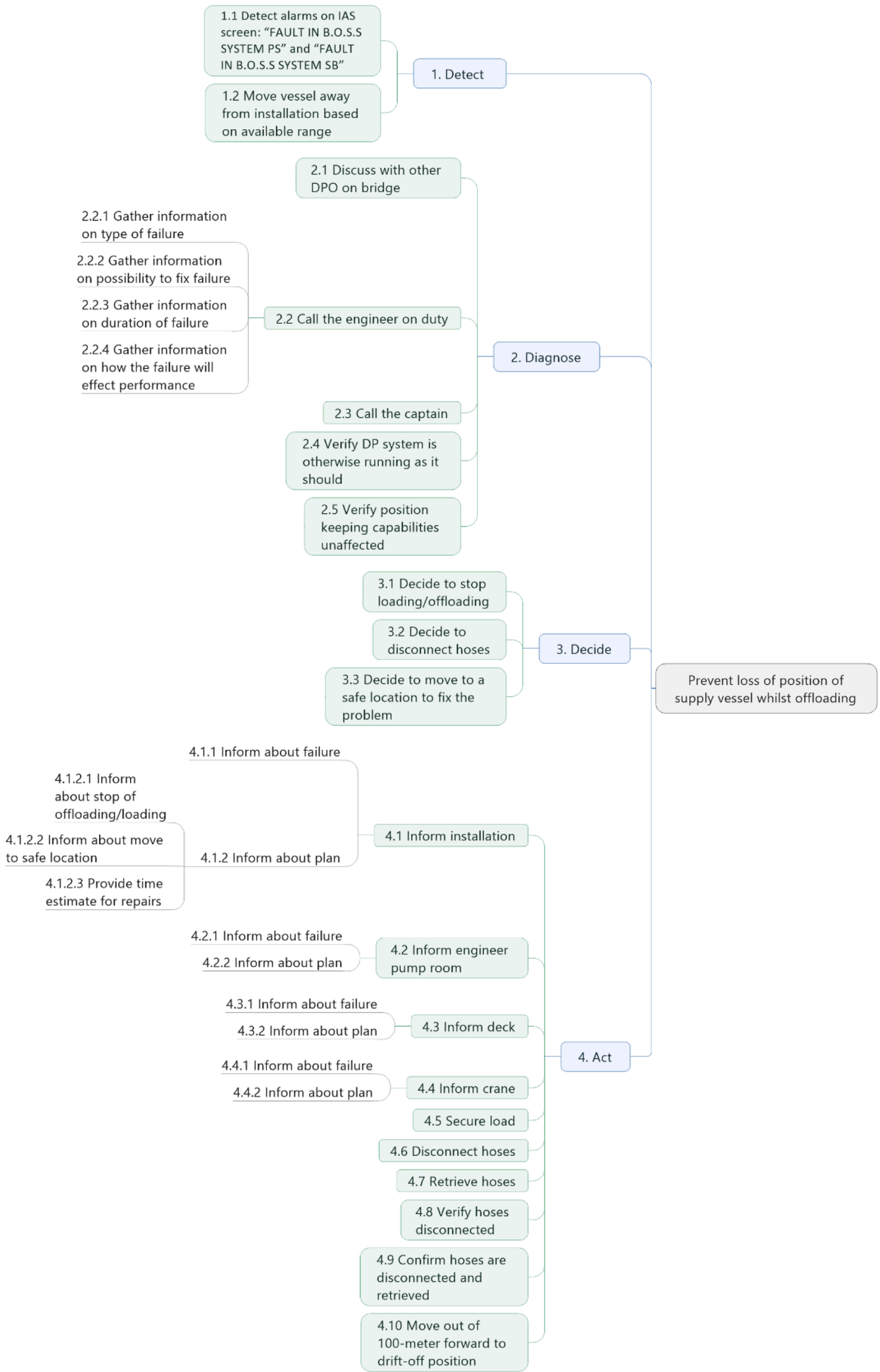

Fig. 4. Hierarchical Task Analysis (HTA) of the early warning scenario based on events of the Sjøborg accident.

Table 5
Tabular Task Analysis (TTA) of the early warning scenario based on events of the Sjøborg accident data obtained and verified in interview. * CP = critical path.

#	Task	Responsible	Cue	Order of CP*	Simultaneously with	Time estimate per interview (in seconds)			Comment
						1	2	3	
1.	Detect								
1.1.	Detect alarms on IAS screen: “FAULT IN B.O.S.S SYSTEM PS” “FAULT IN B.O.S.S SYSTEM SB”	DPO1	Visual and auditive alarm.	1		1	1	1	Presented on other screen, possible DPO does not monitor this actively, and will be informed about this by engine room. This scenario assumes the DPO detects the alarm.
1.2.	Change heading of vessel away from installation based on available range of hoses	DPO1	Proximity to installation and potential for escalation of situation.	2	Task 2.1	40	40	40	Size of move depends on slack in the hose and crane operations. Speed also dependent on weather. This would happen after you find out the meaning and consequences of the alarms.
2.	Diagnose								
2.1.	Discuss with other DPO on bridge	DPO1 and DPO2, highest rank on bridge if available	Task 1.1.	3	Task 1.2	0	5	15	Discuss potential loss of redundancy and escalation of situation. Discussion is held with relevant personnel on the bridge, but as a minimum between DPO 1 and DPO 2.
2.2.	Call the engineer on duty	DPO2	The engineer does not know the cause of the error.	4		10	15	30	This will take a bit longer, the DPO will request the engineer to consult with the electrician and find out of problem. If this happens during the night shift, the electrician will be in bed and needs to come down first. Uncertain how much time it will take for engineer to come to phone.
2.2.1.	Gather information on type of failure	DPO2 and engineer							
2.2.2.	Gather information on possibility to fix failure	DPO2 and engineer							
2.2.3.	Gather information on duration of failure	DPO2 and engineer							
2.2.4.	Gather information on how the failure will effect performance	DPO2 and engineer							
2.3	Call Captain	DPO2						5	Call to inform about the failure and the unknown cause of the failure. The captain will come to the bridge.
2.4.	Verify DP system is otherwise running as it should	DPO1	Position plot, alarms, thruster and power use, reference systems, consequence analysis.						
2.5.	Verify position keeping capabilities unaffected	DPO1	Position plot, alarms, thruster and power use, reference systems, consequence analysis.						
3.	Decide	Highest rank on bridge	Task 2.2.	5	Task 2.2.	1	15	15	Time is dependent on if the DPOs agree, or not.
3.1.	Decide to stop loading/offloading	Highest rank on bridge	Task 2.2.						
3.2.	Decide to disconnect hoses	Highest rank on bridge	Task 2.2.						No problems with position keeping so the DPOs will decide to take the time to disconnect.
3.3.	Decide to move to a safe location to fix the problem	Highest rank on bridge	Task 2.2.						Safe location is preferred to be within the 500 meter zone if the engineer and DPO think the problem can be repaired locally and relatively quick, to avoid reentering procedure. The safe location is always in a drift off position relative to the installation and other vessels/objects on the field, and at least a 100 meters away from the installation and other vessels/objects on the field (if relevant).
4.	Act								There is no real hurry, the vessel is still capable of position keeping, but the DPOs do not know if this will change, therefore the operation will be aborted safely and efficiently.

(*continued on next page*)

Table 5 (*continued*)

#	Task	Responsible	Cue	Order of CP*	Simultaneously with	Time estimate per interview (in seconds)			Comment
						1	2	3	
4.1.	Inform installation CCR	DPO2	Task 2.2. and Task 3.	8	Task 4.6	15	5	5	Informed last when the abled bodies on deck and crane driver have started the disconnect.
4.1.1.	Inform about failure	DPO2	Task 2.2. and Task 3.						
4.1.2.	Inform about plan	DPO2	Task 2.2. and Task 3.						
4.1.2.1.	Inform about the stop of offloading/loading	DPO2	Task 2.2. and Task 3.						
4.1.2.2.	Inform about the move to safe location	DPO2	Task 2.2. and Task 3.						
4.1.2.3.	Provide time estimate for repairs	DPO2	Task 2.2. and Task 3.						
4.2.	Inform engineer pump room	DPO2	Task 2.2. and Task 3.					5	Engineer is listening on radio.
4.2.1.	Inform about failure	DPO2	Task 2.2. and Task 3.						
4.2.2.	Inform about plan	DPO2	Task 2.2. and Task 3.						
4.3.	Inform deck	DPO2	Task 2.2. and Task 3.	7		5	5	5	On same frequency as crane driver and bridge.
4.3.1.	Inform about failure	DPO2	Task 2.2. and Task 3.						
4.3.2.	Inform about plan	DPO2	Task 2.2. and Task 3.						
4.4.	Inform crane	DPO2	Task 2.2. and Task 3.	6			5	5	This will take a bit longer, because the crane driver can be difficult to reach on radio. Crane operation will take longest therefore informed first.
4.4.1.	Inform about failure	DPO2	Task 2.2. and Task 3.						
4.4.2.	Inform about plan	DPO2	Task 2.2. and Task 3.						
4.5.	Secure load	Deck and crane driver	Task 4.3. and Task 4.4.						
4.6.	Disconnect hoses	Deck	Task 4.3.	9		20	20	30	Time required is dependent on the location of the crane. For this scenario, it is assumed that the crane is positioned over the deck of the supply vessel.
4.7.	Retrieve hoses	Deck and crane driver	Task 4.3. and Task 4.4.	10		15	30	30	
4.8.	Verify hoses disconnected	Deck	Task 4.2.						
4.9.	Confirm hoses disconnected and being retrieved	DPO1	Visually out window and on CCTV.	11		1	1	1	
4.10.	Move out 100-meter forward into a drift-off position	DPO1	Task 4.9.	12		120	120	120	Use joystick to move out. When in a drift-on position it is not allowed to go from DP to manual within two ship lengths of installation, for a drift off position, this limit is one ship length. The Sjøborg was in breach with this limit when the alarms were received.

they need to move immediately, after which DPO 1 changes the DP system to manual mode and tries to move to a safe location with the remaining thruster capacity. The time estimate of the move to the safe location does not reflect the environmental forces working against the vessel and the lack of thruster capacity per se. This would slow the move down. However, the most important goal is to avoid collision and move away from the installation. At this point of the scenario the duration is of the task is less relevant.

3.3. Perceived time available and perceived time required

Perceived time available and perceived time required estimates were obtained with an electronic questionnaire distributed among DPOs with supply vessel experience. The survey was distributed via a survey monkey website link and was completely anonymous. The sample of 88 participants had the following characteristics: age: 22 reported between 25-34 and 31 between 35-44, 24 reported between 45-54, and 11 reported between 55-64. On gender: 87 reported male, one was not comfortable reporting gender. On position: 30 reported DPO, 28 reported Chief Officer, 26 reported Captain, 3 Marine Traffic Controller and one person failed to state current position. On years of experience as DPO (or higher) on a supply vessel: M = 12 (SD= 7; N=87) years, nationality: 74 Norwegian, 11 Swedish and 3 Finnish.

The participants were provided with the following scenario description:

"The scenario is based on the Sjøborg incident that took place at the Statfjord A platform June 2019. A description of the scenario is presented below, we ask that you answer the questions solely based on the information provided below and that you ***do not consider*** *other knowledge you might have about the incident.*

Fresh water, diesel oil and deck cargo were being transferred from a supply vessel to a platform in the North Sea. The platform is a production and drilling facility with three concrete shafts (see Figure). The Supply vessel has an equipment class 2 DP system, the vessel is 86 meters long and 19.6 meters broad, with a specified displacement of about 7 300 tonnes at that time. The supply vessel has a battery system was installed on the main deck.

The supply vessel was in position on the southern side to discharge deck and bulk cargoes. The vessel lay on the windward (weather) side, with its bow pointing west. The weather was given as 11 meters/second of wind with a direction of about 210 degrees and a significant wave height (Hs) of 1.4

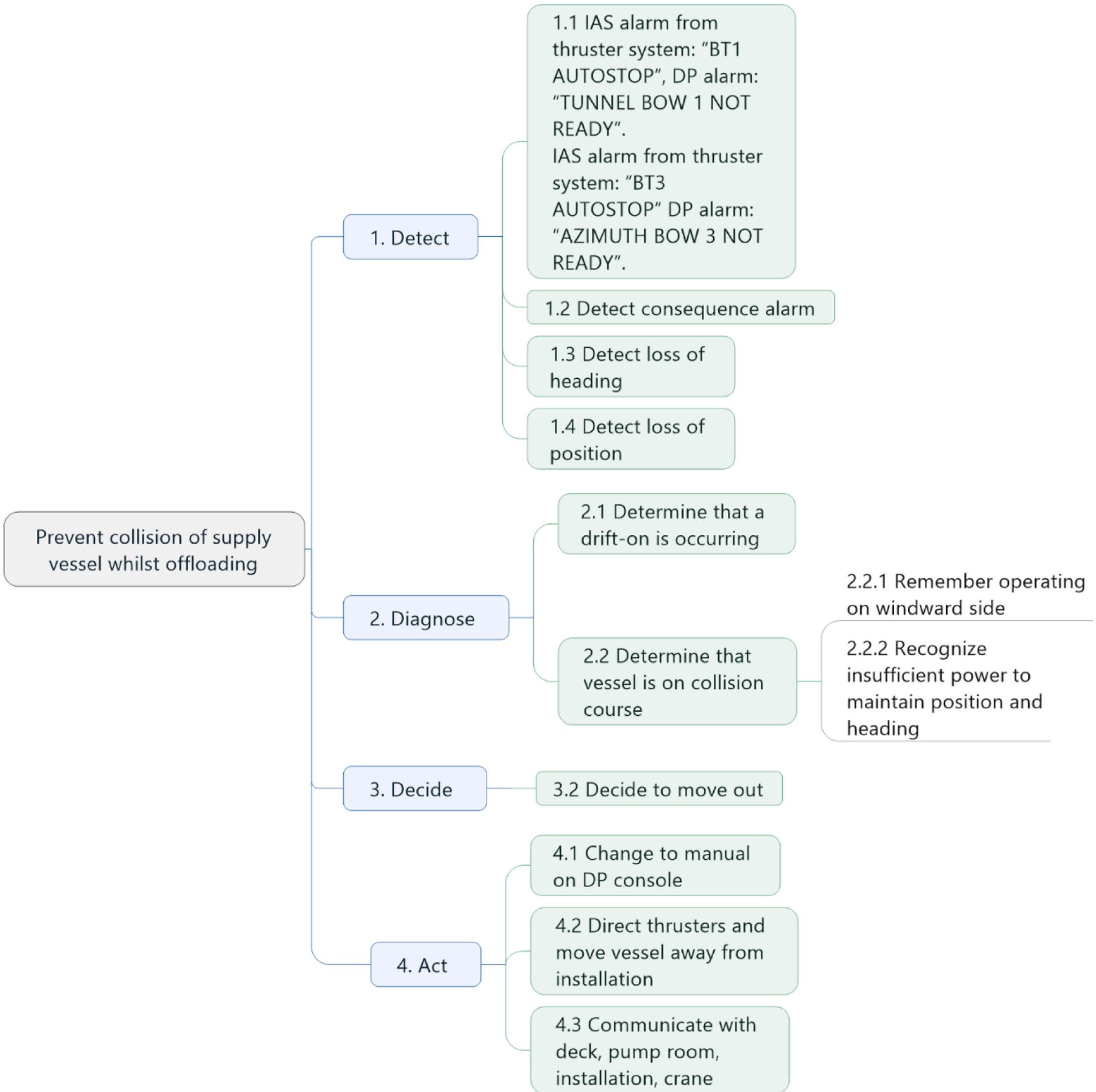

Fig. 5. Hierarchical Task Analysis (HTA) of recovery scenario based on events of the Sjøborg accident.

meters. The power supply system was configured with one generator on the port main switchboard segment and the battery system on the starboard side, while the isolator switch between the switchboard segments was in the closed position. A technical fault meant the load reduction mode was activated on the vessel, reducing power to all its thrusters to 10-15 per cent of the maximum. At about 01.50, power was lost to two of three bow-thrusters.

Below a timeline of the events is presented."

Time	*Event*
00.24	*Vessel positioned 5-6 meters aft of and 2 meters away from the platform structure. That gave better access to deck cargo.*
01.04	*Alarms on IAS screen: "FAULT IN B.O.S.S SYSTEM PS" and "FAULT IN B. O.S.S SYSTEM SB".*
01.14-01.49	*Several DP alarms at regular intervals: "HEADING OUT OF LIMITS" "THRUSTER PREDICTION ERROR" "CONSEQUENCE ANALYSIS BATTERY BTY TIME ALARM"*
01.49	*DP system change to move vessel 6 meters forward for access to deck cargo. IAS alarm from thruster system: "BT1 AUTOSTOP", DP alarm: "TUNNEL BOW 1 NOT READY". IAS alarm from thruster system: "BT3 AUTOSTOP" DP alarm: "AZIMUTH BOW 3 NOT READY".*

They were asked to answer the following questions based on the scenario description only:

- IF the supply vessel was to collide, how long time do you think it will take before the vessel reaches a point of no return or collides? ESTIMATE IN SECONDS
- IF the supply vessel was to collide, how much longer time do you think the DPO needs to avoid a collision? ESTIMATE IN SECONDS
- Any comments? (OPEN TEXT)

3.3.1. Results perceived time available

Data analysis showed that out of the 88 participants there were 17 outliers in the data spread over the perceived time available and time required. The outliers were removed from the data set, leaving 71 participants. The average perceived time available before the vessel would collide or cross a point of no return was $M = 32$ (SD = 24; N = 67). The dataset showed that the variance between the conditions was not significantly equal. Despite this, multivariate analyses were conducted including age, experience and position as independent variables and

Table 6
Tabular Task Analysis (TTA) of recovery scenario based on events of the Sjøborg accident data obtained and verified in interview. * CP = critical path.

#	Task	Responsible	Cue	Order of CP*	Simultaneously with	Time estimate per interview (in seconds) 1	2	3	Comment
1.	Detect								
1.1	IAS alarm: "BT1 AUTOSTOP", DP alarm: "TUNNEL BOW 1 NOT READY" "BT3 AUTOSTOP" DP alarm: "AZIMUTH BOW 3 NOT READY"	DPO1		1		1	1	15	Call engine room, to find out what happened, this can take additional time dependent on where the engineer is. Not obvious from HMI, will have to check status of thrusters to see they have actually stopped.
1.2	Detect consequence alarm								
1.3	Detect loss of heading								
1.4	Detect loss of position								
2	Diagnose	DPO1	Task 1.1	2		1	30	30	Discuss with DPO2, register that you lost 2 thrusters and that the vessel will drift/is drifting.
2.1	Determine that a drift-on is occurring								
2.2	Determine that vessel is on collision course								
2.2.1	Remember operating on windward side								
2.2.2	Recognize insufficient power to maintain position and heading								
3	Decide	DPO1	Task 2	3		1	1		Decision-making is considered a part of diagnosis time. Senior DPO will take the decisions, even when not on DP.
3.1	Decide to disconnect								Secondary concern (dangerous situation for deck hands, this worries the DPO and could affect the chosen solution)
3.2	Decide to move out								Primary concern, consider joystick/manual dependent on speed of drift off, if slow than joystick gives you more control, but less thrust. Manual you risk moving, at first, a bit closer to the installation before you can use full power away
4	Act	DPO1	Task 3						
4.1	Change to manual on DP console			4		1	1	1	
4.2	Direct thrusters and move vessel away from installation			5		120	120	120	
4.3	Communicate with deck, pump room, installation, and crane.	DPO 2	Task 3	6	Task 4.1 and 4.2	120	120	120	This is as assumption, has to be simulated. Have to come to a drift-off position. This is a minimum

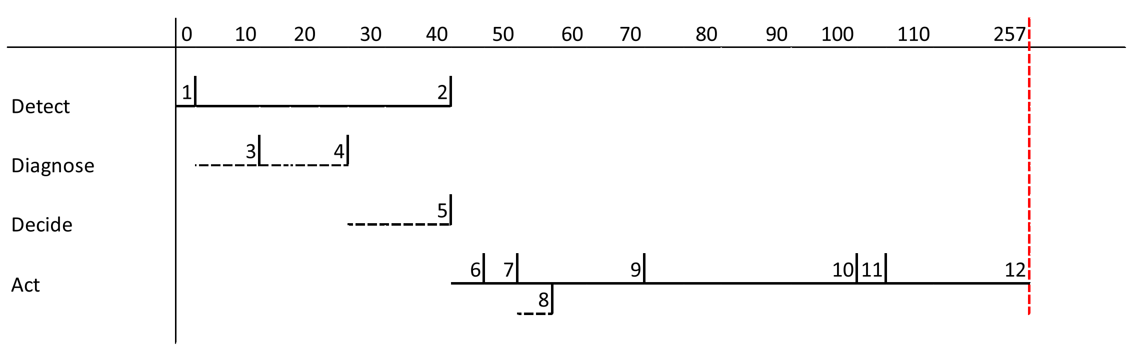

Fig. 6. Timeline critical path tasks (see Table 5) time required scenario 1: early warning based on the Sjøborg accident.

perceived time available and perceived time required as dependent variables. None of the effects were significant.

3.3.2. Results perceived time required

The average estimated time required for the DPO to avoid a collision was $M = 21$ (SD = 14; N = 66).

A non-parametric test (Related Samples Wilcoxon Signed Rank Test) was performed to compare the means of perceived time available and perceived time required. The analysis showed that the means differ significantly $p < 0.05$. This means that the perceived time required was significantly less than perceived time available, which would result in most participants estimating that they would be able to avoid a collision.

3.4. Time required as human response time (HRT) model

3.4.1. Detection and diagnosis

Palmer, Horowitz, Torralba and Wolfe [20] conducted an experiment to capture response time distribution of visual tasks including feature searches, conjunction search, and spatial configuration search. In this research, the ability of four functions to capture the resulting empirical RT distribution is evaluated, and Gamma distribution is suggested as one of the functions that fits well to the data. The detection and

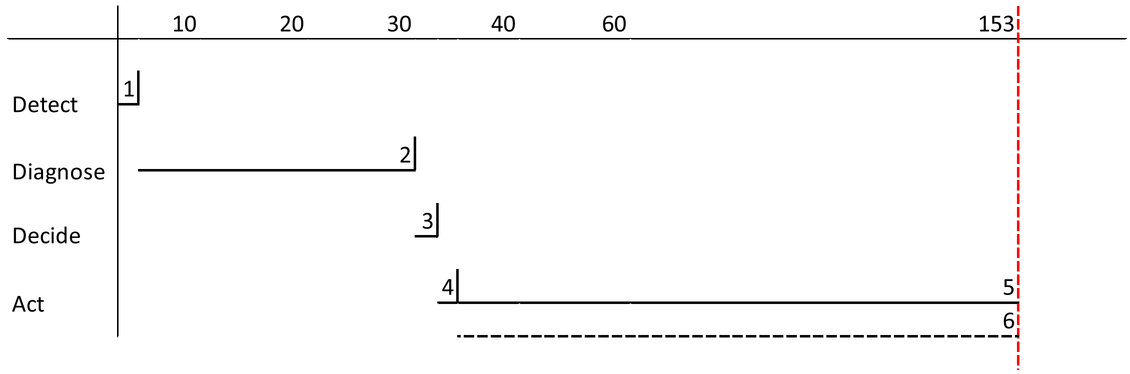

Fig. 7. Timeline critical path tasks (see Table 6) time required scenario 2: recovery based on the Sjøborg accident.

diagnosis process in a DP operation is a combination of the tasks presented in this research. Thus, gamma distribution is used to evaluate detection and diagnosis response time.

The gamma distribution is a two-parameter category of continuous probability distributions. Eq. (1) presents a general form of the gamma distribution. The gamma distribution can be parameterized in terms of a scale parameter α and a shape parameter β.

$$f(x|\alpha,\beta,\xi) = \frac{(x-\xi)^{\beta-1}\exp\left(\frac{x-\xi}{\alpha}\right)}{\alpha^{\beta}\Gamma(\beta)} \tag{1}$$

The shape and scale parameters are defined based on Chen, Moan and Vinnem [6]. In this research, experiment data on response time in DP systems are provided for FPSO–ST offloading operations. The HRT model in this paper uses the response time data to predict the response time for a drift-off on a shuttle vessel; it assumes that the response time is transferable since the operator is operating a nearly identical system. Limitations associated with this assumption are explained in the discussion section of this paper.

The response time data from the study from Chen, Moan and Vinnem [6] show that etection and diagnosis of driving off approximately takes 59 seconds. Based on these data, the shape and scale parameters for detection response time are 2 and 400, respectively. Fig. 8 presents the shape of the gamma distribution with these parameters, and the mean value of 23.1 seconds.

This graph presents the probability plot of the time required for detection. The values on the Y-axis are probability × 10e4, e.g., number 200 on Y-axis presents 200/(10e4=0.02).

Fig. 9 presents the probability distribution of diagnosis response time that follows the gamma distribution. As mentioned, the shape and scale parameters are defined based on data provided in Chen, Moan and Vinnem [6]. The shape and scale parameters of the distribution is equal to 1.5 and 850, and the mean value is 37.3 seconds.

The probability distribution of detection and diagnosis is presented in Fig. 10. The mean value of the distribution is 60.1 seconds. Chen, Moan and Vinnem's [6] study reported a mean value of 59 seconds for the decision-making and diagnosis time for handling a drive-off during a FPSO-ST offloading operation.

3.4.2. Decision-making and execution

The allocated time to the decision-making and execution process is stochastic. According to Ma, Holden and Serota [17], the best distribution that fits human response time is the generalized inverse gamma distribution. In probability theory and statistics, the generalized inverse Gaussian distribution (GIG) is a three-parameter category of continuous probability distributions with probability density function. The general form of the GIG distribution is presented in Eq. (2).

$$f(x) = \frac{(a/b)^{p/2}}{2K_p(\sqrt{ab})}x^{(p-1)}e^{-(ax+b/x)/2}, \quad x > 0, \tag{2}$$

Where, Kp is a modified Bessel function of the second kind, a > 0, b > 0 and p are real parameters of the function. In this study, the allocated time to the decision-making and execution process is assumed to follow the GIG distribution.

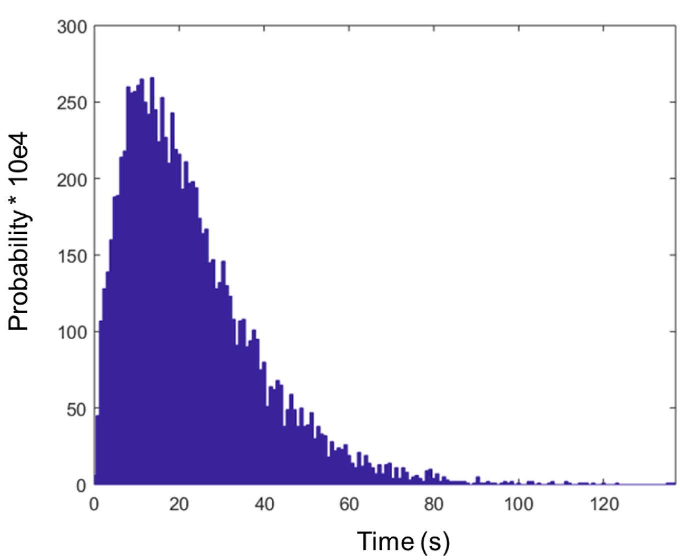

Fig. 8. The probability distribution of detection response time.

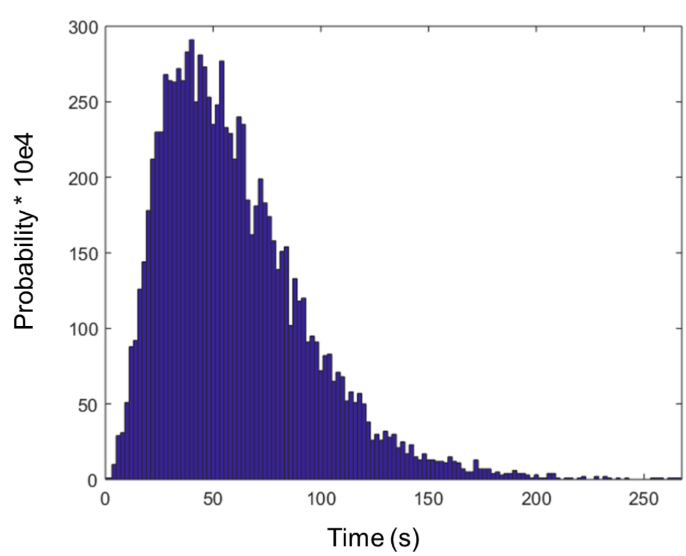

Fig. 9. The probability distribution of diagnosis response time.

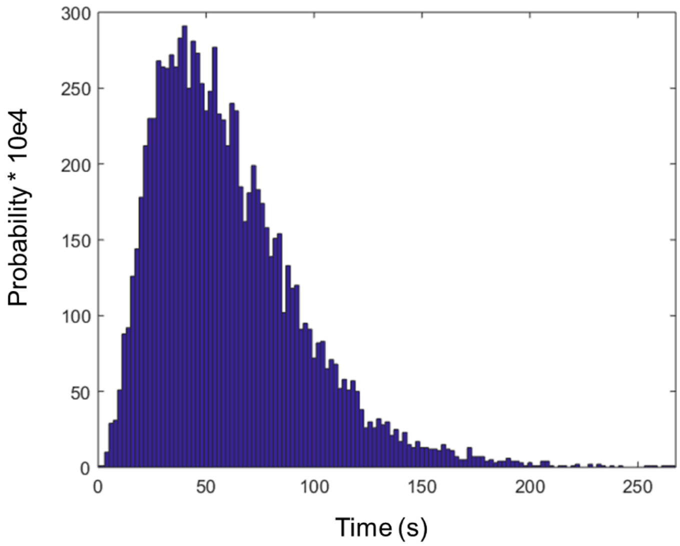

Fig. 10. The probability distribution of detection and diagnosis response time.

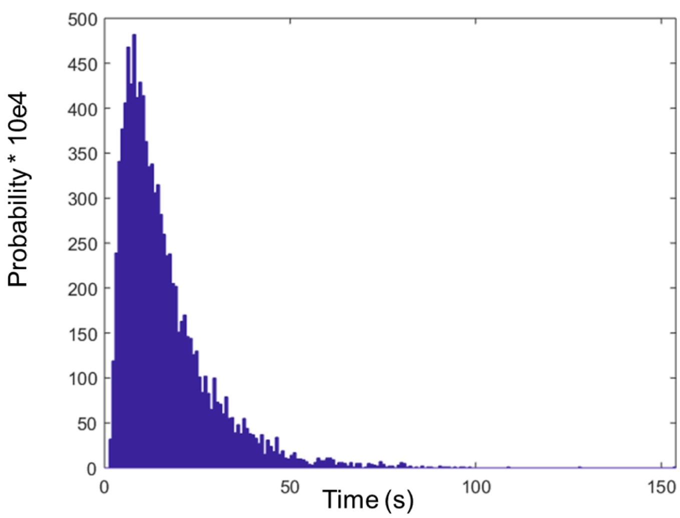

Fig. 11. The probability distribution of decision-making response time.

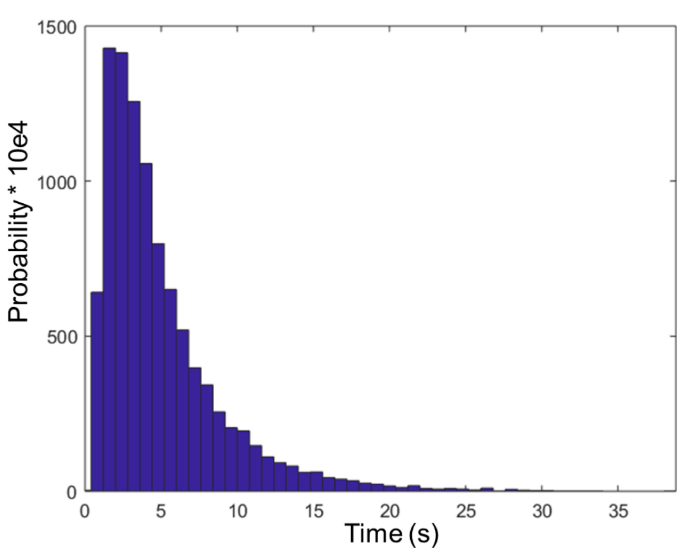

Fig. 12. The probability distribution of execution response time.

For the decision-making process, a, b and p are considered to be equal to 1, 2.5, 1 respectively. These factors give a narrow tail that shows there are some decision-making process that may take longer time. In addition, these factors give the mean value of the decision-making distribution equal to 16.2 seconds, which is in the range of required time for decision-making process, according to Chen, Moan and Vinnem [6]. The probability distribution of decision making response time is presented in Fig. 13.

The response time of execution follow GIG distribution as in previous stages. However, as the required time for this step is shorter than decision-making, a, b and p parameters are considered equal to 2, 1 and 1, respectively.

The distribution probability of decision-making and execution time is presented in Fig. 13. The mean value of the distribution is 21.5 seconds. Chen, Moan and Vinnem's [6] study reported a mean value of 22 seconds for the decision-making and execution time for handling a drive-off during a FPSO-ST offloading operation.

3.4.3. *Total reaction time*

Fig. 14 presents the probability distribution of reaction time that includes detection, diagnosis, decision-making and execution phases. The mean value of the distribution is 81.9 seconds (SD = 36.49; Variance = 1332). Chen, Moan and Vinnem's [6] study reported a mean value of 81 seconds for the total response time for handling a drive-off during a FPSO-ST offloading operation.

Confidence intervals on the mean of the response time are presented in Table 7. Confidence interval is an interval for which we can assert, with a given degree of confidence, that it includes the true mean value being estimated. The confidence interval could be calculated as:

$$\overline{X} \mp Z\frac{SD}{\sqrt{n}} \tag{3}$$

$\overline{X}$ is the mean; Z is the z-value, presented in Table 7; SD is the standard deviation; n is the number of samples, which is equal to 10,000

4. Discussion

4.1. *Comparison of the applied methods and results*

Table 8 summarizes the findings from the various time analyses presented in the previous section.

The time available based on the STEP analysis of the case study for

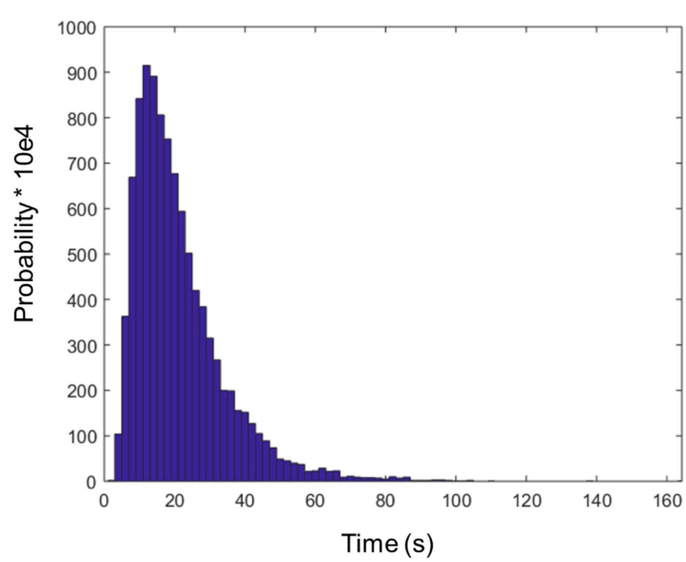

Fig. 13. The probability distribution of decision-making and execution response time.

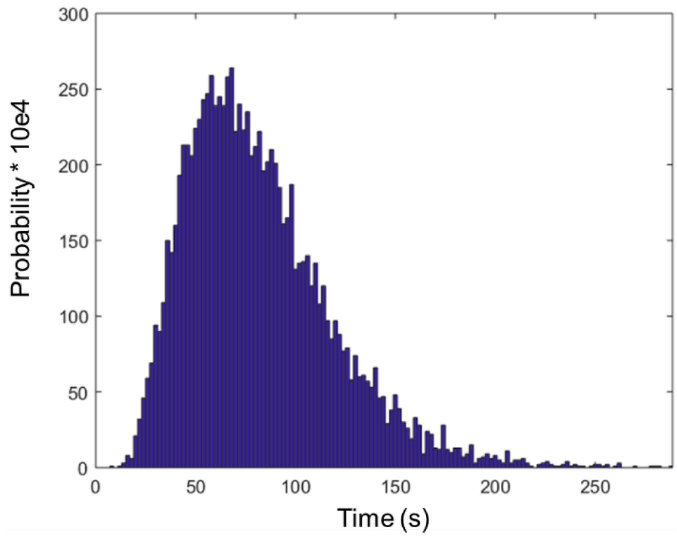

Fig. 14. The probability distribution of total response time.

Table 7
Confidence intervals for the mean of total reaction time.

Confidence Interval	Z-value	Value
80%	1.28	81.9±0.47
85%	1.44	81.9±0.53
90%	1.64	81.9±0.60
95%	1.96	81.9±0.72
99%	2.58	81.9±0.94
99.50%	2.80	81.9±1.02
99.90%	3.29	81.9±1.20

Table 8
Overview of analyses and time estimates in seconds.

Analysis	Detection time	Diagnosis time	Decision time	Execution time	Total time
Section 3.1: Timeline analysis incident report (time available) - Early warning scenario					2220
Section 3.1: Timeline analysis incident report (time available) – Recovery scenario					120
Section 3.2: Timeline analysis (time required) – Early warning scenario	41	50	10	181	257
Section 3.2: Timeline analysis (time required) – Recovery scenario	1	1	1	121	153
Section 3.3: Perceived time available – Recovery scenario					32 (SD = 24; N = 67)
Section 3.3: Perceived time required – Recovery scenario					21 (SD = 14; N = 66)
Section 3.4: Human Response Time model (time required) – Recovery scenario	23	37	16	5	82

the early warning scenario (2220 seconds) and the time required for handling such a scenario (257 seconds, based on median estimates) highlight the fact that the accident could have been prevented if proper action was taken then, there was sufficient time to do so. However, when comparing the estimates for time required based on the recovery scenario (time available: 120 seconds; time required: 153 seconds based on task analyses (median estimates), or 82 based on the HRT model the margins are less favorable, meaning that the operator has almost no chance of successfully recovering from a loss of position. Please note that the original investigation report only presented the time of the events on a minute scale and not on a second scale, on which the other analyses were performed, and that the scenarios of the investigation report end in collision, whereas the other analysis end-states are a successful recovery.

The estimates provided for the timeline analysis (time required in Section 3.2 and Table 8) are very optimistic, they assume that all actors are alert and available at the time of the situation. Especially the estimates for the early warning scenario, since position-keeping capabilities are not directly threatened, it seems reasonable to assume that more time is taken to diagnose the situation and decide on the course of action. Often pressures are experienced from the installation to continue operations so they can receive and offload all cargo [11], which can influence the decision.

Furthermore, one should take into consideration that the estimates for the execution in the timeline analysis for time required are based on ending up in a safe end-state, which has been defined as a 100-meters away from the installation in a drift-off position. The estimated time to arrive at this location is based on all thrusters being functional. This end-state differs from the end-state of the human response time model, which ends the scenario at the DPO initiating the recovering action and not the arrival at the location. The difference constitutes 120 seconds based on the time required estimates provided in Table 5 and Table 6.

The estimates for perceived time available and perceived time required tell us that the participants believe there is significant more time available than what is required to avoid a collision (see Table 8). The perceived time available is so little that it is unlikely it influences the decision on how to handle a situation like this, or the decision when to initiate action. These responses would have to be almost reflex-like in order to be able to succeed under these time pressures. What is more, this optimism is despite the fact that most participants are likely to be familiar with the Sjøborg accident, and would know that the vessel collided with the installation.

The mean of perceived time available, 32 seconds, is also lower than the time available calculated in the timeline analysis, 120 seconds. This could be due to the participants estimating time available until the point-of-no-return instead of time to collision.

The human response time (HRT) model estimate (82 seconds) indicates that there would have been sufficient time to recover from the loss of position as it was described in the accident investigation report. The accident investigation showed that the DPO was not successful in his first attempt to manually take over and move the vessel away from its collision course. They had to wait for the master to come to the bridge and take over. The master was successful in the manual take over, but was too late to avoid a collision. Furthermore, the HRT estimates are based on data from a study by Chen, Moan and Vinnem [6], which was based on shuttle tanker drive-offs and not supply vessel drift-off. Observational data from various DP operations and incident scenarios need to be gathered to verify the applicability of these results.

In summary, the methods differ in the aspect of time they measure, the STEP analysis is a retrospective analysis based on incident reports where time available is measured. The quality of the analysis is dependent on the quality of the incident investigation report, any uncertainty in the report will be transferred to the STEP analysis. The timeline analysis based on the task analyses analyzes the time required to perform a task or achieve a goal, the quality of the analysis is dependent

on the quality of the task analyses and the representativeness of the time estimates gathered from interviews, observations, simulations, and accident reports. Furthermore, individual and context factors will always vary and the time required estimate is to be viewed as an average. The perceived time available and perceived time required estimates are based on estimates provided in a survey. These estimates are subjective, and are intended as such, however, the interpretation of the question could not be controlled in an online survey resulting in uncertainty regarding the representativeness of the estimates. The human response time model estimates the time required for the operator. Since the input to the model is partially based on reaction time studies for a drive-off on a shuttle tanker, instead for a drift-off on a supply vessel, there is uncertainty regarding the representativeness of the time required estimates. Further research will need to test the hypothesis that these differences do not affect the human response time. The HRT model can dynamically provide models for human response times and integrated them in online risk models.

The majority of the applied methods measure different aspects of time and are therefore not directly comparable. Only the time required measure for the recovery scenario based on the task analyses and the HRT model can be compared. The HRT model estimates that time required is 82 seconds, and the time required based on the task analyses estimates 153 seconds, which is nearly twice as long. This difference can be explained by three causes, or a combination of them. First, the time required analysis based on the task analyses defined the end-state of the scenario as the arrival at the safe location, the time to get to that location was estimated at 120 seconds, leaving only 33 seconds for response time to the loss of position before initiating the move. Second, this estimated response time is optimistic and assumes an operator that is alert, vigilant, and has the confidence to act personally and adequately. Third, the data used in the HRT model is based on a drive-off situation for shuttle tankers, this data might not be representative for supply vessels experiencing a drift-off.

4.2. QRA and HRA methods and time

QRA methods mainly take time in consideration to be able to estimate speed at time of collision. The models are usually simplistic and do not include a human reliability analysis to calculate the probability for human error and the reliability of the human barrier element. By neglecting the human element and the importance of time within the safety of DP operations, QRAs are also preventing the identification of effective risk mitigating measures. Instead, more attention is directed towards structural integrity, since you do what you measure.

QRA analyses should be improved by including the effect of time on the reliability of the human operator. Some of the operational scenarios described in Table 1 do not allow for sufficient time for an operator to respond, meaning that based on the calculations for time required this time simply is not available, leading to an error probability of 1. Having an operator monitoring the system, serving as a last barrier in case of loss of position, is therefore not a functioning barrier. It is important to spread this awareness and avoid a false sense of security and putting unrealistic expectations on the operator. The availability of these analysis results during the planning phase of the operation will allow the operation to install other barriers or change operational set-up increasing the separation distance or excursion tolerance, giving the operator more time to be able to serve as that last barrier against loss of position and avoiding a collision or other negative consequences.

Furthermore, it is important to include the perceived time available and perceived time required into the analysis as well. Few HRA methods take this into account, of the six HRA methods mentioned in this paper, only the SPAR-H and the Petro-HRA consider the effect of perceived time on reliability of the performance of the operator. Only the Petro-HRA method takes into account the effect of optimistic time estimates by the operator. Creating awareness amongst the operators of time available and time required for various loss of position scenarios is critical, because it affects the decision of what kind of exit strategy to utilize. This is important to highlight in both the risk analyses prior to operation as well as during operation and training.

4.3. Automation and decision support design and time

Automation and decision support tools need to be designed with not only focus on what to communicate to the operator and how to communicate that information, but they also need to be thoughtful about when to communicate information. For example, if alarms that are given due to reaching or approaching predefined limits for position excursion do not give the DPO sufficient time to be able to intervene and recover from a loss of position, then either these limits need to be redefined or the operating conditions need to change.

Hollnagel [12] also argues to change the view of decision-making and move the focus from which decision alternative is most optimal to how to implement that decision and when a decision is made. Within the realm of DP operations this means that instead of focusing on whether to intervene or not (which are the only alternatives in the studied scenarios) to focus on how to move or remain on location and when this decision needs to be made. He further argues that this change in view does not only affect the way we view decision-making, but also decision support. His views are supported by this study that demonstrate the importance of time in the decision-process and the need to focus on the "when" of decision-making in decision support tools and risk analyses.

4.4. Training and time

Training of operative personnel in realistic settings is essential in the preparation for them to be able to handle loss of position scenarios. As demonstrated in the time analyses performed and the resulting time estimates, there is very little time available for DPOs to recover from a loss of position before the loss will result in a collision or other serious consequences. Realistic training settings are important for experiencing the time pressures first hand. Moreover, the awareness of the time pressures in a loss of position scenario will also instill the operator with confidence to take early warnings of potential loss of position scenarios more seriously. If they do not act on the early warnings signs, then they could end up in a situation where they have less than 1,5 minutes to prevent a collision.

To understand the time available and time required, DPOs need to be educated about the time the technical system requires to complete certain actions, such as recalibration of the reference systems and turning of thrusters. Furthermore, DPOs need to experience the time available and time required to handle various loss of position scenarios. When teaching about decision-making during these types of scenarios time needs to be highlighted as a critical factor.

4.5. Limitations and future work

The time required analysis is based on only three interview participants, the interview data can be considered saturated, since consensus was reached in the results presented in this paper. However, to obtain more robust results further interviews could be conducted or the results can be supplemented by observations in a simulator. The estimates provided in this study are, therefore, to be interpreted with this limitation in mind.

For the scenario description of the survey for perceived time available and perceived time required was unable to avoid association with the case study: the Sjøborg incident. The authors therefore decided to reference the incident in the description and ask the participants to not base their estimates on what they know about the further course of events. However, their knowledge about the incident has undoubtedly colored their estimates, if not the knowledge that the loss of position incident led to a collision. Further research should therefore consider including a hypothetical scenario, where these factors cannot affect the

estimates of the participants.

The shape and scale parameters of the HRT model are based on the experimental data obtained from a study performed by Chen, Moan and Vinnem [6]. However, as mentioned earlier this data is based on modeling a FPSO-ST drive-off scenario, and this paper assumed that the obtained response time obtained are transferable to the scenario in this paper which models a drift-off on a supply vessel. This assumption is rather weak, because there are several differences in operating conditions between supply vessels and FPSO-ST operations [9]. For example, the distance between the vessel and the collision object varies from, typically 80 meters for shuttle tankers, to as little as 20 meters for supply vessels. This does not only affect time available, but also the perceived stressfulness of the situation, which again can affect performance [2,3]. DPOs on a shuttle tanker received additional warnings about loss of position from changes in tension on the loading hose, which is not available on a supply vessel. These considerations limit the transferability of the results of the HRT model. Additional experimental data on response times for several scenario and operational types needs to be gathered to test the assumption that the data from the study by Chen, Moan and Vinnem can be utilized as input to the shape and scale parameters of the HRT model, modeling different scenarios.

Moreover, future research should look into further developing the HRT model and integrating it with the dynamic simulation. The integration of these two models could present dynamic time required and dynamic time available to an operator. If this research is taken one step further then these values could be included in a general online decision support tool, where time is a critical factor. The online dynamic decision support tool will deliver a better risk picture and will support the dynamic nature of decision-making for DP operations ranging from reactive emergency management to a pro-active approach where decision scenarios could be analyzed and anticipated based on real-time information. One such possibility would be to simulate all alternative decision scenarios and provide an approximate time scale and safety level of each scenario. This would include scenarios that have a simulated time available that exceeds time required as modelled by the HRT model. Another option would be to allow the operator(s) to be informed about the event and sequence probabilities in the near future. This information could help operator(s) to readjust system configuration with improved knowledge about the system, operation and the timeline of future states.

5. Conclusion

In this paper, the importance of time in the risk of DP operations has been highlighted by presenting the analyses of time through several methods based on a case study. Neglecting the various ways in which time influences the safety of DP operations prevents the identification of effective risk reducing measures. More time needs to be spent on educating risk analysists and designers on the importance of all aspects of time. Designers can introduce technological solutions that allow for more time for recovery actions and HMI solutions that support the operator better when working under time pressure. Risk analysts and risk managers need to identify risks related to the time to capture the dynamic nature of risk associated with dynamic positioning operations. Only when time is included correctly the risks can be adequately dealt with. Furthermore, DPOs need to be trained so they understand the relationship between time available, time required, perceived time available and perceived time required and how their work is affected by this relationship. As can be seen from the results of the various analyses presented in this paper the margins between the time that is required and the time that is available are too close and in some cases insufficient. Furthermore, there are also discrepancies between the perceived time available and required that could affect the performance of the operators under similar conditions. Awareness around time available and time required should promote operators to always increase their distance to collision objects as much as possible, to increase time available in case position-keeping capabilities are compromised. Future research into decision support models for DP operations need to integrate time required, time available as prominent, dynamic factors, and need to be risk-based. For example, by integrating the HRT model with a dynamic simulator for vessel movement during DP operations. Supporting operators in their awareness of risk dynamically over time will help operators prevent and recover from loss of position incidents and contribute to safer DP operations.

CRediT authorship contribution statement

Sandra Hogenboom: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Tarannom Parhizkar:** Methodology, Formal analysis, Writing - review & editing. **Jan Erik Vinnem:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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